ON THE RELATION OF SATELLITE VIEWED CLOUD CONDITIONS TO VERTICALLY INTEGRATED MOISTURE FIELDS

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ABSTRACT

The saturation deficit, a moisture parameter which is used in quantitative precipitation forecasting and which is a measure of the mean relative humidity in the layer 1000–500 mb., is related to both satellite-viewed cloud cover and cloud conditions. The results are presented in the form of contingency tables. The positive correlation found between cloud cover and saturation deficit is greatly improved when a distinction is made between deep and shallow cloud conditions.

1. INTRODUCTION

Although there have been recent attempts to use satellite pictures of cloud conditions indirectly to infer vertical motion and related quantities as a means of improving numerical analyses [6], there has been little use of these data to infer the distribution of moisture. A recent study made use of satellite pictures in conjunction with conventional data to estimate relative humidity below 500 mb. in the Gulf of Mexico region with encouraging results [9], but both the area covered and the sample size were small, and the method does not use satellite data *exclusively*.

Knowledge of the horizontal and vertical distribution of atmospheric water vapor, or of the horizontal distribution of the vertically-integrated vapor content of the air, is needed for quantitative precipitation forecasting (QPF), and for including the diabatic effects of latent heat release in numerical forecasting models. The presence of clouds, particularly extensive stratiform clouds, in a given layer is prima facie evidence of saturation conditions there, but determination of the water vapor content requires specification of the mean temperature, or thickness, of the layer as well. To specify the vertical distribution of relative humidity, it is necessary to know the height of the cloud layers being viewed. Even estimating the mean relative humidity through a deep layer (e.g., 1000–500 mb.,) requires some knowledge of the cloud layer distribution in the vertical. Skilled interpretation of satellite-viewed cloud conditions can often yield useful inferences of cloud depth, and radiation values often enable one to calculate the height of the top of the uppermost cloud layer [3].

The purpose of this study was to explore possibilities for obtaining humidity information from satellite pictures alone, since in sparse-data areas even relatively crude estimates may provide useful inputs for numerical forecasting. Satellite pictures enable one to obtain the earth's cloud cover over large areas, and although coverage was incomplete with most of the early TIROS satellites, the satellites of the TIROS Operational Satellite (TOS) System are designed to give full coverage every day.

2. RELATION OF SATELLITE NEPHANALYSIS CLOUD COVER TO SATURATION DEFICIT

The first trial was designed to determine if any relationship existed between cloud cover given in satellite nephanalyses and some measure of the vertically integrated relative humidity. The so-called "saturation deficit" was chosen for the moisture parameter. This quantity, which may be taken as a measure of the mean relative humidity in the layer 1000–500 mb., is currently used in operational quantitative precipitation forecasting. A discussion of the saturation deficit is found in several recent articles [4, 10]. It is defined by the following:

$$h_d \equiv h_5 - h_s$$

where h_5 is the 1000–500-mb. thickness, and h_s is a quantity called the "saturation thickness." The latter is the 1000–500-mb. thickness that would obtain in a layer having a uniform relative humidity of 70 percent, a moist adiabatic lapse rate, and a mass of water vapor equal to the observed precipitable water. The use of 70 percent to indicate saturation of the column is justified by the well-known tendency for radiosonde humidities (lithium chloride element) to be biased toward low values, and by the observational evidence that significant precipitation often begins at approximately this humidity level.[1]

Operational nephanalyses produced at the National Environmental Satellite Center depict the large-scale cloud cover according to the classification shown in figure 1 [7]. This classification is supplemented by code figures for specifying the average size of cloud pattern features (viz.,

[1] Experience with more recent observations in which the carbon humidity measuring element was used indicates that the appropriate nominal value for saturation is now 80–85 percent.

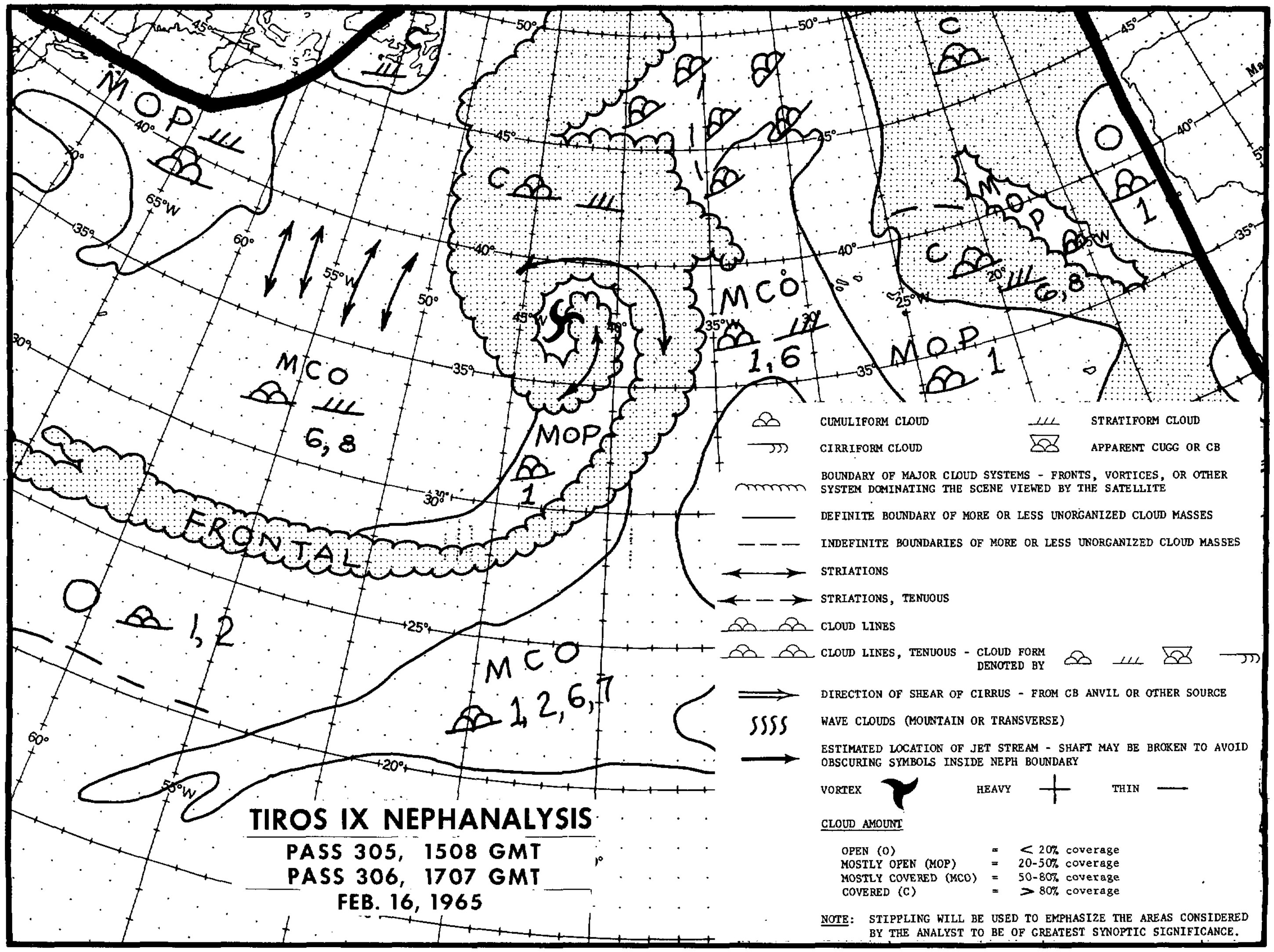

FIGURE 1.—Example of an operational nephanalysis together with definition of symbols and terminology.

cloud masses and open areas), and by symbols designating the general character of the cloudiness (viz., stratiform, cumuliform, cirriform, etc., or combinations of these), and whether they appear bright (thick) or thin. Other than this, no direct interpretation or estimation is made as to the height or thickness of the clouds.

For the first test, satellite cloud cover was obtained at numerical weather prediction grid points over the continental United States east of the 100th meridian, from the TIROS VII and VIII nephanalyses for December 1964 and January 1965, and from the TIROS IX nephanalyses for February 1965. Values of the saturation deficit were interpolated to the nearest 10 m. at the same grid points from numerical analyses of saturation deficit provided by the QPF unit of the National Meteorological Center.[2] The satellite passes over this area usually differed by 3 to 6 hr. from the radiosonde observations, but no time adjustment was made in the first test, the results of which are given in table 1. In the column at the left are the column relative humidities for U.S. Standard Atmosphere temperature conditions; the humidity corresponding to a given saturation deficit depends to a small extent upon thickness, as is pointed out by Younkin et al. [10]. Note, however, that a zero deficit corresponds to a relative humidity of 70 percent by definition.

It is seen that the totals in the contingency table are distributed generally as would be expected if there were a positive correlation between mean relative humidity in the troposphere below the 500-mb. level and cloud amount, i.e., the greater the cloud cover, the higher generally is the humidity value. With the null hypothesis that *no* relation exists between saturation deficit and satellite-viewed cloud amount, a chi-square value of 478 is obtained. Since $\chi^2=37.70$ at the 0.1 percent level, the probability that the distribution given in table 1 is just a chance deviation from the hypothesis is much less than 1 in 1,000. It is seen that a sizable fraction of the "covered" cases are found with moderate to large deficit values

[2] The negligible number of cases in which the saturation deficit was less than −60 m. or greater than 360 m. was grouped in the respective extreme classes.

TABLE 1.—*Relation of satellite nephanalysis cloud cover to saturation deficit*

Relative humidity (U.S. Standard Atmosphere) (percent)	Saturation deficit (Unit: 10 m.)	Cloud cover from satellite nephanalysis								
		Covered (>80%)		Mostly Covered (50–80%)		Mostly Open (20–50%)		Open (<20%)		Total
		No.	Percent	No.	Percent	No.	Percent	No.	Percent	
84–70	−6– 0	193	19.0	19	7.8	7	2.5	5	0.8	224
69–58	1– 6	250	24.5	36	14.7	25	9.0	38	6.3	349
57–48	7–12	220	21.6	47	19.2	62	22.2	98	16.4	427
47–40	13–18	177	17.4	49	20.0	51	18.4	109	18.2	386
39–33	19–24	129	12.7	66	26.9	55	19.8	157	26.2	407
32–21	25–36	49	4.8	28	11.4	78	28.1	192	32.1	347
Total		1018	100.0	245	100.0	278	100.0	599	100.0	2140

(i.e., low humidities). This is not too surprising, however, since the "covered" cases comprise cloud conditions varying all the way from shallow stratus or stratocumulus clouds to very deep nimbostratus-altostratus-cirrostratus cloud systems.

The relationships evident in the contingency table would probably have been sharper had there been smaller time differences between the satellite observations and the upper-air soundings. An indication of the representativeness of the sample is given by the fact that the percent frequencies computed from the initial sample of TIROS VII and VIII data changed very little when the sample size was doubled by adding the TIROS IX data.[3]

3. RELATION OF "COVERED" CLOUD CONDITIONS FROM SATELLITE PICTURES TO SATURATION DEFICIT

The principal weakness evident in the about attempt to relate layer humidity to satellite-viewed cloud amount is that no distinction is made between deep and shallow cloud conditions. In an attempt to remedy this situation, the following trial was devised. The subset of cases from the first trial that were classed as "covered" on the nephanalyses were singled out for picture interpretation. A synoptic meteorologist with experience in the interpretation of satellite pictures can often distinguish between thick layers of solid or multi-layered stratiform clouds and shallow layers of predominantly low or high cloud. The procedure is subjective, of course, being basically similar to that used by a trained, ground-based or airborne observer in classifying cloud types. In classifying cloud conditions viewed from a satellite, however, the analyst gains considerable advantage from the fact that no longer is his view circumscribed by the horizon only a few tens of miles distant. The integrated view over hundreds of miles in all directions, and the location of the given point with respect to organized cloud systems (which are often related to frontal and other circulation features), both are factors that can be brought to bear on reducing the subjectivity in classifying satellite-viewed cloud conditions.

In this trial each case was placed in one of four categories of "covered" cloud condition (see table 2) *exclusively* on the basis of its appearance in the satellite picture. There was no knowledge of the humidity distribution or even of the synoptic situation, except what could be inferred from the picture itself. Figure 2 gives an example of each of the four categories of cloud condition. These are taken from Project Storm Cloud [5] because aircraft and other observations were available to document the cloud structure.

One other change from the first trial was made. Since the saturation deficit is a conservative moisture parameter and its patterns behave in a regular way, a simple time interpolation was used to adjust the h_d values to the time of the satellite pictures.

The results of this test are given in table 3. Although the 916 cases in table 3 are taken from the 1,018 "covered" cases in table 1, 102 cases were omitted because of poor viewing conditions, or because missing saturation deficit data would not permit interpolation to the time of the satellite picture.

TABLE 2.—*Classification of "covered" cloud condition from satellite pictures*

CATEGORY	DESCRIPTION OF "COVERED" CLOUD CONDITION	APPEARANCE OF CLOUD IN PICTURE
A	Very deep, solid or multi-layered *stratiform** cloud. Extends from near earth's surface to at least 500–400 mb.	Broad bands or extensive areas of solid, bright cloud with an amorphous appearance indicative of overlying cirrostratus.
B	Moderately deep, solid or multi-layered *stratiform** cloud. Extends from near earth's surface to about 700–600 mb.	Bands or areas of nearly solid, fairly bright cloud often having a "hard" or "sculptured" look.
C	Predominantly low and shallow *stratiform** cloud.	Bands or areas of mostly solid, mostly dull** cloud that is often somewhat ragged.
D	Predominantly high cirriform or middle-level stratiform cloud.	Bands or areas of mostly solid, generally dull cloud, often fibrous or streaky.
E	Reliable interpretation not feasible.	High nadir angles of view or poor illumination.

*Predominantly stratiform cloud systems may have embedded cumuliform elements.
**Coastal stratus, and occasionally oceanic stratocumulus, may appear rather bright, but their location and characteristic form are usually sufficient to prevent confusion with the other cloud conditions.

[3] Incidentally, it is of interest to note that the column totals in table 1 can be taken as a sort of cloud "climate." It is seen that during these three winter months over the eastern two-thirds of the United States "covered" conditions prevailed nearly half the time, whereas "open" conditions prevailed about one-fourth of the time. The remaining one-fourth of the time was divided about equally between "mostly open" and "mostly covered" conditions. These percentages also proved to be stable with respect to sample size.

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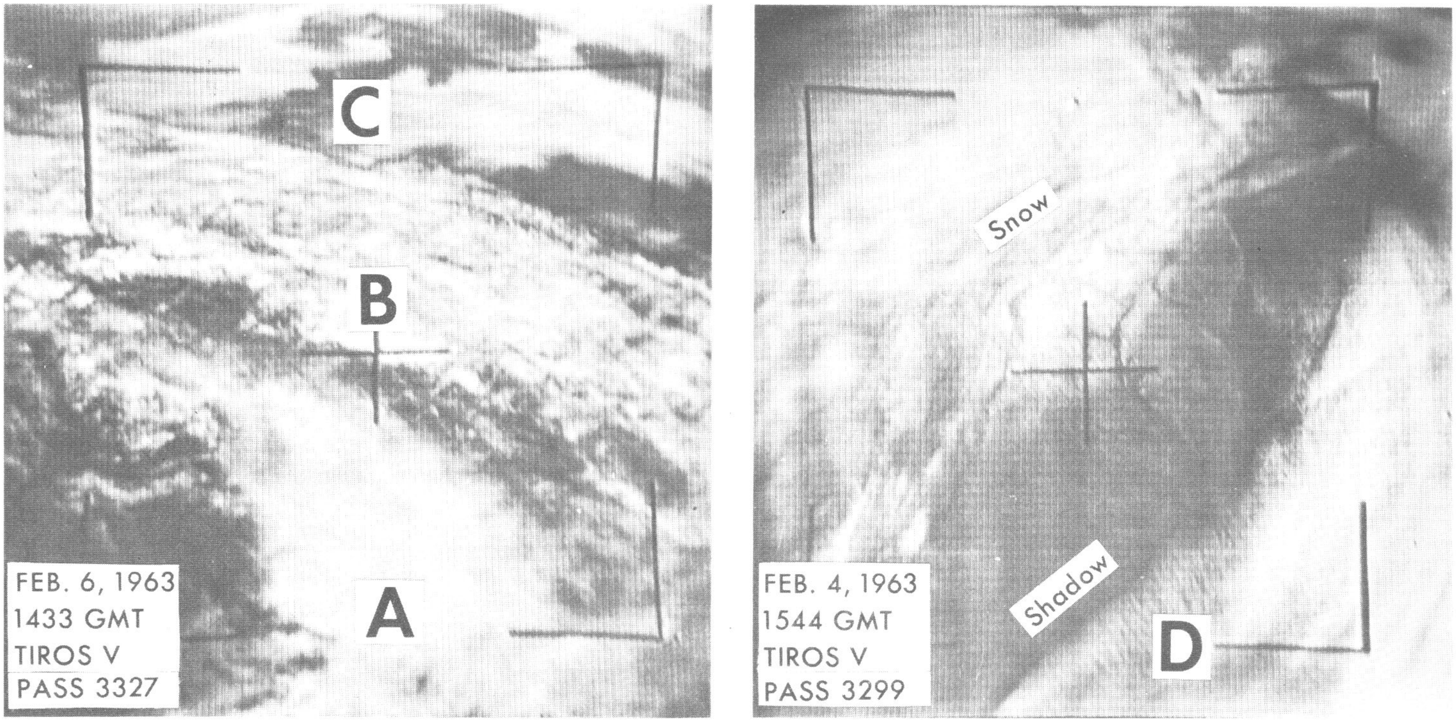

FIGURE 2.—Examples of "covered" cloud condition categories defined in table 2. Left: Type A, B, and C cloud conditions just off the east coast near Cape Hatteras. Right: Type D cloud conditions on the east coast near Chesapeake Bay (note shadow cast by high-level clouds on North Carolina, Virginia, and on the low-level clouds east of the Delaware-New Jersey coasts). Eastern Pennsylvania and the western portions of Maryland and Virginia are snow-covered, but high- and middle-level clouds are present farther to the northwest.

Comparison of tables 1 and 3 clearly reveals that those "covered" cases associated with low relative humidities in table 1 are, in large part, found in the type C and D cloud conditions in table 3. Over 73 percent of the type A cloud conditions were associated with saturation deficits smaller than +60 m., whereas the values drop to 46, 23, and 14 percent for the B, C, and D type conditions, respectively. Conversely, only 8 percent of the type A were found with deficits greater than +130 m., whereas the values are 26, 50, and 59 percent, respectively, for types B, C, and D. A chi-square value of 173 was obtained for the distribution given in table 3, indicating a negligible probability ($\ll 0.001$) that this sample was drawn from a population in which *no* relation exists between saturation deficit and covered cloud conditions interpreted from satellite pictures.

From the above one may conclude that interpreting the satellite cloud photographs as to type of cloud condition results in a considerable sharpening of the relationship between "covered" cloud situations and mean relative humidity in the layer 1000 to 500 mb. One can also conclude from table 3 that the distinction made in table 2, i.e., the separation of covered cloud conditions into four categories, is meaningful in terms of interpretations made from satellite pictures. Were this not so, the relationships in table 3 would not be evident. Strengthening this conclusion is the fact that the cloud condition classification was made without benefit of other meteorological information.

4. CONCLUDING REMARKS

Although it has been shown that a strong positive correlation exists between satellite-viewed cloudiness and layer-mean relative humidity below 500 mb., especially if one uses cloud conditions inferred from pictures rather than simply the cloud amounts taken from operational nephanalyses, the limitations of the data were such that the relationship is perhaps even stronger than indicated. In the first place, although the TIROS VII and VIII pictures were good from the standpoint of resolution, they were poor in terms of coverage. In general, the more complete is the coverage of a cloud system, the more reliable will be the interpretation of the cloud conditions comprising it. TIROS IX, which was the first of the so-called "TIROS Wheel" satellites [8], was in a much higher orbit than intended, so coverage was very great, but resolution was rather low. Good picture quality and resolution are important for meaningful interpretation of cloud type. Secondly, although an attempt was made in the second trial to allow for the 3–6-hr. time difference between radiosonde and satellite observations, it would be more satisfactory if a trial were run in which this time gap was reduced to 2 hr. or less. This would reduce

TABLE 3.—*Relation of "covered" cloud condition from satellite pictures to saturation deficit*

Relative Humidity (U.S. Standard Atmosphere) (percent)	Saturation deficit (Unit: 10 m.)	Cloud Condition from satellite picture								
		A Very deep solid or multi-layered stratiform cloud		B Mod. deep solid or multi-layered stratiform cloud		C Predominantly low and shallow stratiform cloud		D Predominantly high or middle stratiform cloud		Totals
		No.	Percent	No.	Percent	No.	Percent	No.	Percent	
84–70	−6– 0	55	32.6	60	14.5	13	4.6	0	0.0	128
69–58	1– 6	69	40.8	131	31.6	53	18.7	7	14.3	260
57–48	7–12	32	18.9	112	27.1	75	26.4	13	26.5	232
47–40	13–18	12	7.1	76	18.3	79	27.8	14	28.6	181
39–33	19–24	1	0.6	29	7.0	50	17.6	10	20.4	90
32–21	25–36	0	0.0	6	1.5	14	4.9	5	10.2	25
Total		169	100.0	414	100.0	284	100.0	49	100.0	916

errors in humidity estimates made in regions of strong horizontal gradients. Further reduction of this type of error could be achieved by the use of station values of saturation deficit rather than interpolations at grid points from machine analyses of saturation deficit.

5. FUTURE STUDIES

New tests designed to incorporate the considerations discussed above are planned for use in conjunction with the ESSA I satellite, which was placed in orbit on February 3, 1966. This satellite, the first of the TOS System, has been returning pictures of good quality and resolution, and there have been very few gaps in coverage.

Since moisture estimates from satellite data would be most useful in areas where radiosonde data are scanty or absent, trials will be run using sounding data from ship, island, and coastal stations. If stations are chosen in the eastern Pacific or eastern Atlantic, then satellite times are within 2 hr. of sounding times. It is planned to test the reproducibility of the cloud condition interpretations by having several meteorologists, after instruction, independently categorize a number of cases according to the scheme shown in table 2. Also being developed and tested is a *numerical* classification of cloud conditions as viewed from satellites. This scheme, which comprises ten categories, takes into account both cloud *condition* and cloud *cover*, and it is not restricted to predominantly stratiform cloud systems.

Longer-range goals include experiments with high-resolution and medium-resolution infrared radiation data to increase the objectivity of the cloud condition determinations and possibly to provide some vertical resolution in the humidity determinations. Digitized cloud picture data in the form of average cloud cover and cloud brightness normalized to specified area sizes also will be incorporated into the technique as soon as these data become available [1]. A beginning has been made in the area of relating thickness patterns to satellite-viewed cloud patterns [2], and this work is continuing. Eventually it may be possible to make the entire process automatic from the satellite raw data input to a moisture data output that is in suitable form for further use in numerical weather analysis and prediction.

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